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ABSTRACT

The fluxes of heavy nuclei with $Z \geq 6$ in the primary cosmic radiation were measured with a nuclear emulsion stack exposed in a balloon flight over Texas on March 26-27, 1962, and the fluxes of M($6 \leq Z \leq 9$) and H($Z \geq 10$) nuclei extrapolated to the top of the atmosphere were found to be 6.20 ± 0.46 and 2.02 ± 0.25 particles/m^2 ster sec, respectively. Results of this work and those of other investigations made during the last solar cycle (1954-1964) are used to study the long term solar modulation of primary S-nuclei ($Z \geq 6$) of rigidity ≥ 4.8 BV. It is found that the lag between the primary intensity changes and the sunspot number is about one and a half years during the increasing phase of solar activity and is very small during the declining phase of solar activity. This is in agreement with the changes of the spectral shape during the solar cycle as suggested by Simpson. The implication of the time lag in terms of the scale size of the transition region of the magnetic field responsible for the long term modulation is briefly discussed.

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THE FLUX OF HEAVY NUCLEI IN THE PRIMARY COSMIC RAYS OVER TEXAS IN MARCH 1962, AND THE SOLAR CYCLE MODULATION

INTRODUCTION

The study of fluxes of heavy nuclei in the primary cosmic rays with energies $\gtrsim 1.6$ Bev/nucleon incident on Texas (geomagnetic latitude $\lambda \approx 41°$) is of interest from two considerations. Firstly, from the comparison of the fluxes measured over Texas with those measured simultaneously at a low geomagnetic latitude, e.g. near the equator, one can obtain a two point integral energy spectrum of the different components and compare them in the energy range of about 1.6 to 7 Bev/nucleon. Secondly, from the comparison of the fluxes of heavy nuclei measured over Texas at different times over the solar cycle, the long term solar modulation of the primary heavy nuclei of rigidity $\gtrsim 4.8$ BV may be investigated. With these objectives in mind a nuclear emulsion stack was exposed over Texas on March 26-27, 1962. Simultaneously another emulsion stack was exposed over Hyderabad, India by the group at the Tata Institute of Fundamental Research, Bombay. The preliminary results from the Texas stack were reported previously (Neelakantan and Biswas, 1963). Using the initial results from the Texas stack and the Hyderabad stack, the integral energy spectrum of the heavy nuclei in the energy interval 1.6 to 7 Bev/nucleon was obtained (Badhwar et al. 1963). This aspect of the problem will not be discussed further in this paper. Here we present the final results of the analysis of the heavy nuclei in the Texas Stack, the comparison of these flux values with those of other investigators obtained during the solar cycle (1954-64), and a discussion of the long term solar modulation of primary heavy nuclei of rigidity $\geq$ 4.8 BV.

EXPERIMENTAL PROCEDURE

The experiment was conducted with an emulsion stack flown in a balloon flight over Texas on March 26-27, 1962. The balloon floated for 14.5 hours at 5.55 g/cm^2 of residual atmosphere. The time-altitude curve and the trajectory of the balloon are shown in Figures 1a and 1b, respectively. An arrangement to provide rotation of the stack by 90° upon reaching ceiling failed so that the flipping occured at the time of launch. Standard nuclear emulsion techniques were used in the analysis of the stack, the details of which are given in the appendix.

Since the cutoff rigidity allows the tracks to be considered as relativistic, charge identification was made by at least two independent ionization measurements on each particle track. The ionization measurements were made by δ-ray counting in the G5 emulsions and blob-gap counting in the G2 emulsions by three different observers. Using this technique to obtain an average Z- value, 185 M nuclei, and 66 H nuclei were detected. Correcting for scanning efficiency this gives 195.7 M nuclei and, 66 H nuclei at the scan line.

RESULTS

The observed fluxes of M and H nuclei were extrapolated to the top of the atmosphere by the following two methods. Firstly in the extrapolation procedure using diffusion equations, we use the values of interaction mean free paths in air for M and H nuclei as 27.1 and 18.9 g/cm^2 respectively and the best available values of fragmentation parameters, P_{MM}, P_{HM}, and P_{HM} obtained as 0.15, 0.32, and 0.23 respectively from the weighted average values measured in graphite, celluloid and teflon (Durgaprasad, 1963; Friedlander et al., 1963). These values are in general agreement with those used by other investigators (e.g., O'Dell et al., 1961) for an air like medium. The fluxes thus obtained after correcting for particles recorded during the ascent and extrapolated to the top of the atmosphere are

$$J_M(0) = 6.20 \pm 0.46 \text{ particles/m}^2 \text{ ster sec}$$

$$J_H(0) = 2.30 \pm 0.28 \text{ particles/m}^2 \text{ ster sec}$$

$$J_S(0) = 8.50 \pm 0.54 \text{ particles/m}^2 \text{ ster sec}$$

It should be pointed out here that in case of H nuclei, the diffusion method predicts the absorption mean free path of H nuclei in air as $\Lambda_H = 24.5$ g/cm^2 which is smaller than that of M nuclei $\Lambda_M = 31.9$ g/cm^2, so that, the ratio of H/M in the atmosphere should increase with atmospheric depth. However, the observed H/M ratio as a function of the atmospheric depth is found to be slowing decreasing or almost constant as shown by Daniel and Durgaprasad (1962) and Webber (1965). As pointed out by these authors, the diffusion procedure probably breaks down in the case of H nuclei because of the fact that the group is so large. Therefore, the second procedure is used to obtain the extrapolated flux for H nuclei. Thus the observed ratio of H/M at the flight altitude (after correcting for ascent particles) and the observed growth curve of H/M in air as given by Webber (1965) are used to obtain the $(H/M)_0$ ratio at the top of the atmosphere. Then the $J_H(0)$ value at the top of the atmosphere is determined by using the $J_M(0)$ as obtained previously. The fluxes thus obtained are

$$J_M(0) = 6.20 \pm 0.46 \text{ particles/m}^2 \text{ ster sec}$$

$$J_H(0) = 2.02 \pm 0.25 \text{ particles/m}^2 \text{ ster sec}$$

$$J_S(0) = 8.22 \pm 0.52 \text{ particles/m}^2 \text{ ster sec}$$

In any case, since the measurements were made at small atmospheric depth (5.55 g/cm^2), the above two different extrapolation procedures yield results which are similar.

COMPARISONS WITH OTHER INVESTIGATIONS

The available data on the flux of (M + H) nuclei measured over Texas at atmospheric depth of $\leq$12 g/cm^2 by different investigators are given in Table I. Before comparing these results, the following two points should be considered. Firstly, different investigators have used different methods and parameters for the extrapolation of the measured fluxes, particularly for the H-nuclei. The absorption mean free path of H-nuclei in air, Λ_H, used by different authors vary widely from 24 to 54 g/cm^2. For M-nuclei, however, most of the authors have used nearly the same value of Λ_M as $\sim$32 g/cm^2. In order to compare different measurements correctly, it is important to normalize them using the same extrapolation procedure. Therefore, we have obtained the J_M' (0) and J_H' (0) fluxes of different investigators using the same method of extrapolation, namely the second procedure given in the previous Section. The normalized fluxes J_S' (0) are shown in column 9 of Table I. Secondly, most of the investigators of the Texas experiments assume the geomagnetic cut-off energy as 1.5 Bev/nucleon or cut-off rigidity as 4.5 BV, irrespective of the trajectory of the balloon. We have calculated the effective cut-off rigidities for our balloon trajectory as well as those of other investigators who have given their balloon trajectories, taking into account the variation of the cut-off rigidity with geographic location during the flight as given by Quenby and Wenk (1962) and assuming an exponent 1.5 for the integral energy spectrum. The effective geomagnetic cut-off rigidities are also shown in Table I. Since the average cut-off rigidity for these flights is about 4.8 BV, we have normalized J_S' (0) flux values to the same cut-off rigidity of 4.8 BV. The final normalized fluxes, J_S'' (0), are shown in the last column of Table I and these are used for further analysis.

SOLAR CYCLE VARIATION

Next we consider the variation of the flux of primary heavy nuclei of $Z \geq 6$ of rigidity $\geq$4.8 BV during the last solar cycle, 1954-1964. So far, a number of investigations have been made on the solar cycle variation of the flux of low energy primary protons and helium nuclei of rigidity 0.9-3 BV (See, for example, Summaries by Webber, 1962, 1965; Freier and Waddington, 1965) and relatively less has been discussed on the long term modulation of heavy nuclei of rigidity ≥ 4.8 BV. In studying the long term solar modulation of the heavy nuclei we have taken the flux of M + H nuclei as a whole so that statistical errors are reduced and the uncertainties if any, in the separation of M and H nuclei in different experiments do not enter.

The available data on the normalized flux of (M + H) nuclei of rigidity ≥ 4.8 BV, as given in Table I, have been plotted against Mt. Washington neutron monitor counting rate, in Figure 2. It is seen that most of the flux measurements were made during periods close to either solar maximum, (Mt. Washington rate about 2000) or to solar minimum (Mt. Washington rate about 2400) and very few data are available for intermediate periods. The data point from the present work is the only one available for the period of intermediate neutron monitor counting rate. The variation shown in Figure 2 is different from that shown by Webber (1965) because in the latter the preliminary value of the flux obtained in the present work was used. Also we have neglected the flux value measured by McDonald and Webber (1962) on 20th March, 1956, which was included in Webber's Figure 13 because this measurement was made during a period of large Forbush decrease (McDonald, 1957). Since in some Forbush decrease events the rigidity dependence is different from that due to the 11 year modulation (Webber, 1962; Kane, Wincker and Arnoldy, 1965) it is important that Forbush decrease events should not be included in the study of the long term variation. The regression curve given by Webber (1965) would predict the flux of (M + H) nuclei at the time of this investigation as 7.0 particles/m^2 ster sec, which is more than two standard derivations lower than the measured value. Although a nearly linear regression curve cannot be ruled out completely on the basis of the single data point, the nonlinear regression curve shown in Figure 2 is indicative of the feature that nuclei of rigidity $\geq$4.8 BV seem to recover faster than the Mt. Washington neutron monitor which responds to all particles of rigidity greater than 1 BV. This is consistent with the neutron monitor data available at present, as discussed below.

In order to study in more details the changes of the heavy primary flux of rigidity $\geq$4.8 BV with the increasing and decreasing phases of the solar activity we have plotted in Figure 3, the fluxes of the S nuclei for the years 1954-1963, together with the solar activity in sunspot number in the inverse scale. As seen in the figure, during the increasing phase of the solar activity from 1954 to 1957-58, a number of measurements of the S nuclei flux are available which show that between solar minimum in 1954 and solar maximum in 1957, the S nuclei flux decreased by as much as 45 percent below the 1954 level. It also shows that the decrease in the primary flux lagged behind the increase of solar activity (as given by the sunspot number), the amount of lag being a function of time. During the low and intermediate period of solar activity this lag was about one and one-half years and this lag seems to decrease as the maximum of the solar activity is reached. This behavior is of similar pattern to that shown earlier by Simpson (1963) and by others (Webber, 1965; Waddington, 1965) of the counting rate of the Mt. Washington neutron monitor (responding to particles >1 BV). The lag of the latter with respect to sunspot number during the same period of the solar cycle was about one year which is nearly the same as that observed here for the S-nuclei. The minimum of the Mt. Washington neutron monitor and of the S nuclei flux both seem to occur very close to the maximum of solar activity.

During the decreasing phase of the solar activity, there are unfortunately very few data on the flux of S nuclei of rigidity $\gtrsim 4.8$ BV, the present work being the only measurement available at present between the years 1958 to 1962. Hence, subject to this limitation, the inferences would be only suggestive and much in need of further verification. The fluxes measured in this experiment in 1962 and by Webber (1965) in 1963 are nearly the same within statistical errors indicating that by 1962-63 the flux of S nuclei recovered to a large extent and was only a few percent below the 1954 level. This suggests that during the decreasing period of solar activity in 1958 to 1963, the flux of S nuclei seems to follow more closely the solar activity as given by the sunspot number, as opposed to the behavior of the high latitude neutron monitor which shows a large lag of about two years during 1960-1962. This is consistent with the general picture given by Simpson (1963) which indicates that during the recovery phase, neutron intensity changes produced by primary particles with rigidity greater than 2.8 BV recovered faster than those produced by particles with rigidity greater than 1.5 BV and the equatorial neutron counting rate produced by particles of rigidity greater than 14 BV recovered almost fully to 1954 value during the end of 1961 and early 1962.

Another way of examining the lag is to plot the flux or its percentage decrease below 1954 level against the mean sunspot number as shown in Figure 1. This shows the characteristic "hysteresis" effect (Simpson, 1963), and how the phase lag is changing over the solar cycle. Here again the lack of data points between the years 1958-1962 makes the recovery phase during the years 1958-62 uncertain. The rigidity dependence of the modulation as discussed earlier would produce a hysteresis loop such that, the higher the rigidity, the smaller would be the area under the hysteresis loop.

In the last sunspot cycle the onset of modulation for S nuclei of rigidity $\geq$4.8 BV appears to occur at a solar activity level given by a sunspot number of about 100, whereas the recovery for the same particles appears to have occurred by the time the sunspot number reached 50. Within the limits of the data these results agree with the estimates one would obtain from Simpson's data (1963).

Similar behavior can be seen in the α-particle fluxes measured over Texas during the solar cycle 1954-1963 as given by Freier and Waddington (1965). Here also the scatter of the points are large as statistical errors are considerable and there is a lack of data points between 1959 and 1963 so that the declining cycle is not well known. We wish to point out that from solar minimum (1954) to solar maximum (1957), the flux of α-particles of rigidity $\gtrsim$4.8 BV decreased from 90 to 65 particles/m^2 ster sec, i.e. a decrease of about 28% below 1954 level in contrast to 45% for S nuclei. This difference is not understood at the present if it cannot be attributed to statistical fluctuations, as He and S nuclei have about the same mass to charge ratio and hence are expected to be modulated in a similar manner. Further studies are needed to clarify this effect.

Thus we have the overall picture which seems to indicate that during the increasing phase of the solar activity, all primaries of rigidity >1 BV and $\geq$4.8 BV decrease in a somewhat similar manner with a lag of one to two years with sunspot number, the lag being greater for particles of higher rigidity, while during the declining phase of solar activity, the corresponding lag decreases as the rigidity of the particle increases. This is consistent with the changes in the spectral shape of the primary radiation for the periods 1954-1958 and for 1958-1962 as given by Simpson (1963). The study of the changes of the spectral shape and the intensities over the entire solar cycle provides important clues regarding the origin and structure of the magnetic fields which lie beyond the orbit of the earth and one can estimate the scale size of the transition region from the characteristic build-up and decay times as discussed by Simpson (1963). Unfortunately the data on S-Nuclei fluxes during the declining phase of solar activity are much too sparse to draw any conclusions regarding the depth of the modulating region although the data are not inconsistent with the estimates made by Simpson based on neutron monitor studies over a range of rigidities. The estimates by Simpson and others by

Parker (1963) and Axford et al. (1963) based on termination of solar plasma by galactic magnetic field range from 10-90 A. U.

Appendix

The emulsion stack consisted of 69 Ilford G5 and 7 G2 emulsions of size 20 x 15 x 0.06 cm. Each G5 emulsion was interleaved after every 10th G5 emulsion in the stack. Each emulsion sheet was scanned on a line 5 cm away from the top edge of the emulsion for all tracks crossing the scan line and satisfying the following criteria:

Ionization $\geq$16 times minimum

Projected length in emulsion $\geq$1.9 mm

Zenith angle $\leq 50°$.

Only tracks with projected length $\geq$2 mm and with zenith angle $\leq$45 degrees were finally selected for measurement. The primary tracks with $Z \geq 5$ were separated from slow particle tracks by following the tracks through several emulsions. Then the selected tracks were followed back to the top of the stack and those which came from interactions above the scan line were rejected.

Since the geomagnetic cut-off energy over Texas is about 1.6 Bev/nucleon, all particles entering the stack can be considered relativistic. Hence their charge was determined by making two separate ionization measurements: (i) The long δ-rays which projected at a distance $>1\mu$ from either side of the stack were counted. About 300 δ-rays were counted on each track to determine its charge. The δ-ray counting criteria was kept constant by recounting on some standard tracks frequently. (ii) Blob-gap counting was made on all tracks which passed through a G2 emulsion and belonged to $L(3 \leq Z \leq 5)$ and $M(6 \leq Z \leq 9)$ groups of nuclei as determined from δ-ray density measurements. About 300 blobs and 300 gaps of length $>1.5\mu$ were counted on each track. Plate to plate normalization of the blob density in G2 plates were made in the usual manner. This method was adopted for an independent charge determination for these nuclei in order to obtain reliable separation of L and M groups of nuclei. The charge calibration was done in the standard manner by means of tracks showing charge indicating interactions.

On all heavy nucleus tracks at least two independent charge determinations were made from measurements of at least two different observers. Thus out of 286 tracks of heavy nuclei measured, four independent charge determinations were made on 29 tracks, three independent determinations on 135 tracks, and two independent determinations on 122 tracks. In general there was good agreement between these charge assignments, excepting a few cases. In these cases mean charge was assigned on the basis of the average of the independent determinations. The cross plot of the charges determined by δ-ray density and blob gap method is shown in Figure 5. Thus using all the available measurements good charge resolution was obtained between L and M nuclei as well as between M and H nuclei $(Z \geq 10)$. No attempts were made to determine individual charges of nuclei belonging to the H group ($Z \geq 10$). The charge distribution as obtained from all the measurements is shown in Figure 6.

A total of 34 L nuclei, 185 M nuclei and 66 H nuclei were obtained in the scan length of 240.5 cm and in scanned area of 13.60 cm^2.

The scanning efficiencies of the five scanners who scanned the emulsions were determined by rescanning of the plates by a different scanner, and these were found to be 100%, 100%, 88%, 96% and 80% for M nuclei and 100% for H nuclei. No attempt was made to analyze the L nuclei and the scan criteria were not chosen to efficiently accept this group. The weighted average of the scanning efficiency for M nuclei was 94%. After correcting for scanning efficiency, the number of M nuclei was 195.7 and of H nuclei 66.

Acknowledgments

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Table I

Fluxes of M and H Nuclei of Rigidity ≥4.8 BV

Serial No.	Authors	Date	Mt. Washington Neutron Monitor	Mean Sunspot Number	J_M (0)	J_H (0)	J_S (0)	J_S' (0)	Effective geomagnetic cut-off from Trajector (BV)	J_S'' (0)
					Fluxes of the top of atmosphere, particles/m² ster sec			Normalized to the same extrapolation method*		Normalized flux with rigidity ≥4.8 BV
1.	Yagoda (1956)	Dec. 15, 1952	2380	25	5.5 ± 1.0	2.2 ± 0.5	7.6 ± 0.5	7.6 ± 1.0	5.0	8.1 ± 1.1
2.	Waddington (1957)	Sept. 14, 1954	2460	8	6.1 ± 0.6	2.5 ± 0.3	8.6 ± 0.7	8.8 ± 0.7	4.6†	8.3 ± 0.7
3.	Daniel and Durgaprasad (1961)	Feb. 6, 1956	2420	97	6.7 ± .49	2.1 ± 0.3	8.8 ± 0.5	8.5 ± 0.5	5.1	9.2 ± 0.5
4.	Engler et al. (1958)	Feb. 6, 1956	2420	97	6.1 ± 0.6	2.2 ± 0.4	8.3 ± 0.6	7.6 ± 0.6	5.1	8.2 ± 0.7
5.	McDonald and Webber (1962) (Webber, 1965)	Aug. 17. 1956	2415	149	—	—	8.4 ± 0.8	8.4 ± 0.8	4.6††	7.9 ± 0.8
6.	Frier et al. (1959)	Oct. 19, 1957	2062	199	5.1 ± 0.5	1.7 ± 0.3	6.8 ± 0.6	6.6 ± 0.6	4.7	6.4 ± 0.6
7.	Van Heerden and Judek (1960)	Mar. 9, 1958	1875	201	3.6 ± 0.2	1.11 ± 0.1	4.7 ± 0.3	4.6 ± 0.3	**	(4.6 ± 0.3)
8.	McDonald and Webber (1962) & Webber (1965)	Aug. 1, 1958	1975	184	—	—	5.4 ± 0.6	5.4 ± 0.6	4.6††	5.1 ± 0.6
9.	Garelli et al. (1960)	Sept. , 1958	2015	183	4.4 ± 0.4	1.6 ± .2	6.0 ± 0.4	5.6 ± 0.4	**	(5.6 ± 0.4)
10.	Present work	Mar. 26, 1962	2210	38	6.2 ± 0.5	2.0 ± 0.3	8.2 ± 0.5	8.2 ± 0.5	4.8	8.2 ± 0.5
11.	Webber and Ormes (1963) & Webber (1965)	July 4, 1963	2320	25	—	—	7.3 ± 0.6	7.3 ± 0.6	4.6††	6.9 ± 0.6

*See text
†Measured cut-off
††Instrumental cut-off
**Trajectory not given by authors

Figure Captions

Figure 1: (a) The time altitude curve of the balloon flight. (b) The balloon trajectory.

Figure 2: A plot of the data in Table I giving the flux of S-Nuclei versus the Mt. Washington Neutron Monitor during the most recent solar cycle (1954-1964).

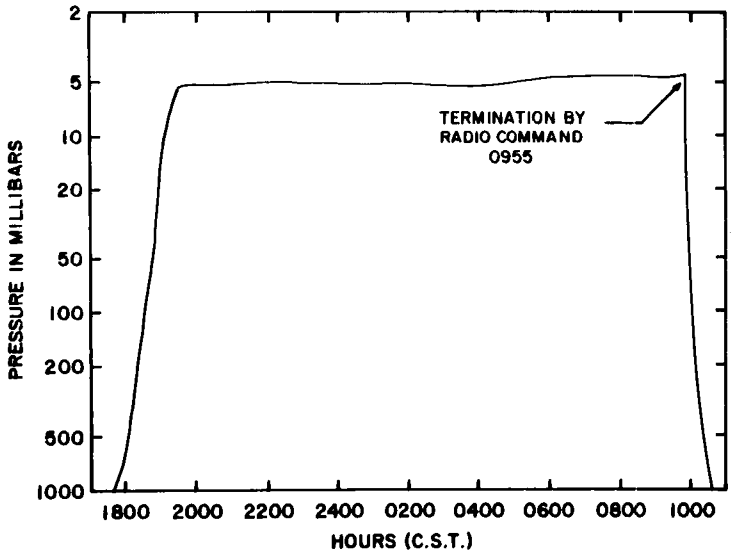
Figure 3: The S-Nuclei flux (⊙) and the smoothed sunspot number (x) plotted as a function of time during the solar cycle.

Figure 4: The flux of S-Nuclei plotted as a function of the smoothed sunspot number during the last solar cycle (1954-1964).

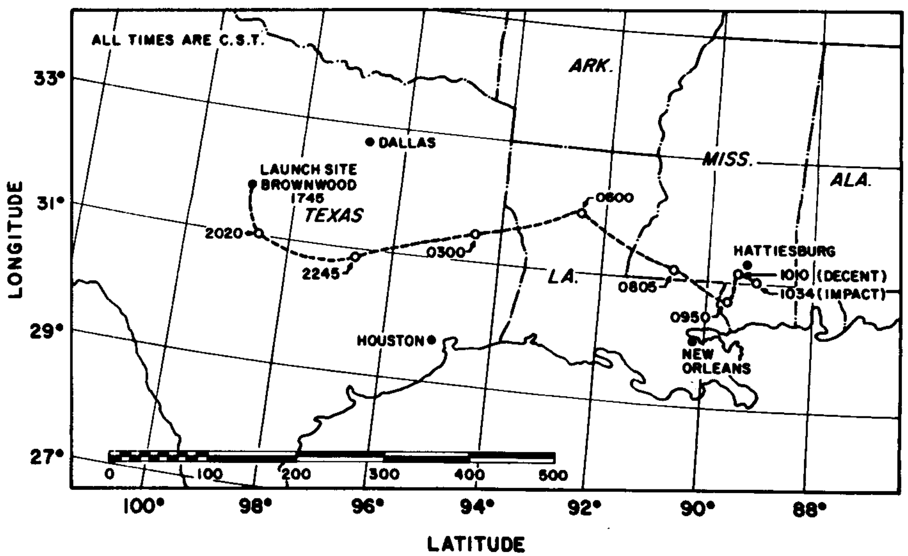
Figure 5: A comparison of the charge assignments made on the basis of blob-gap counts versus those made from delta-ray measurements (N_δ)

Figure 6: The charge distribution obtained using the averaged z-measurements described in the text. No attempt was made to efficiently detect and analyze the charges less than 6.

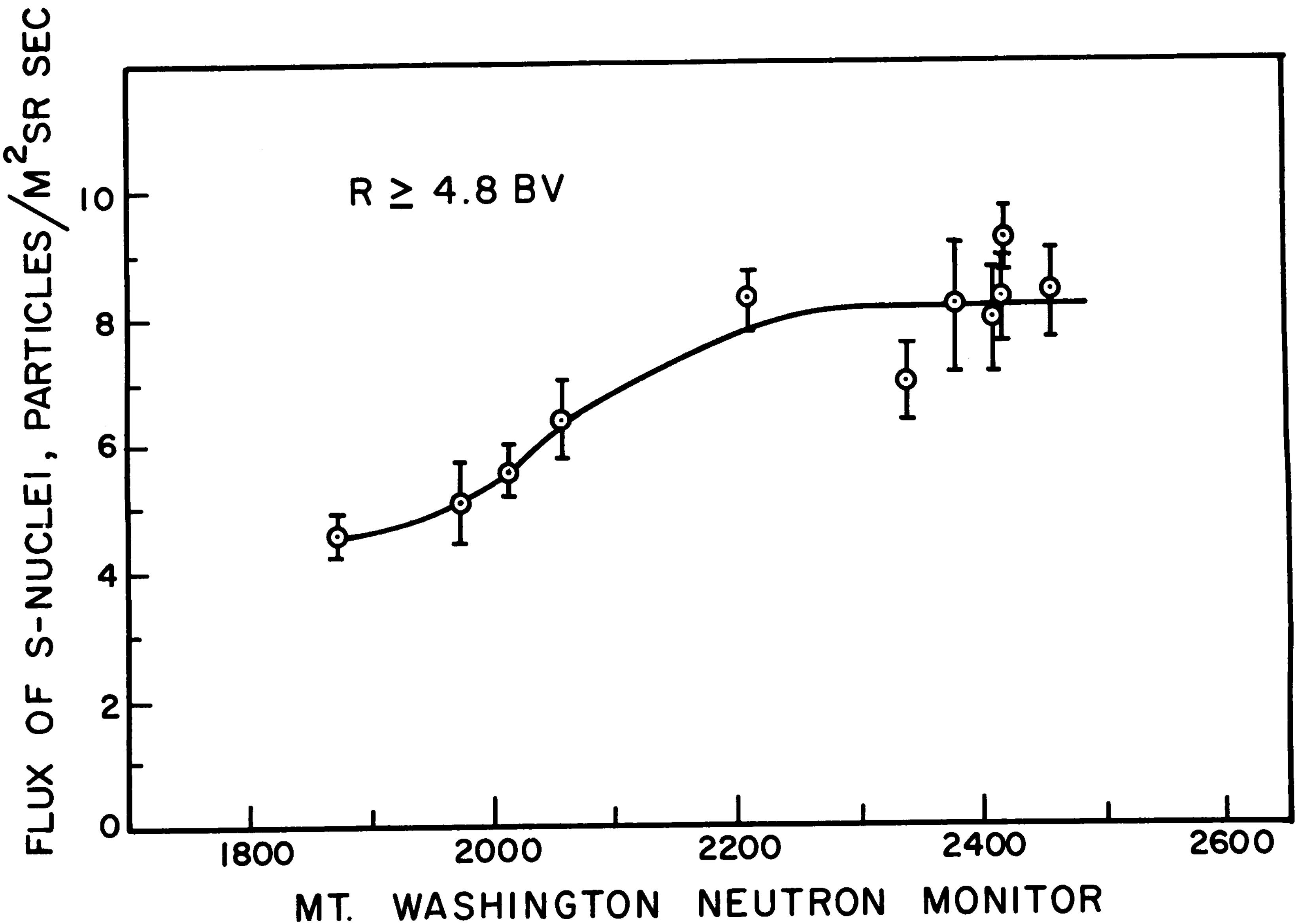
FLIGHT NO. 592-N, 26-27 MARCH 1962

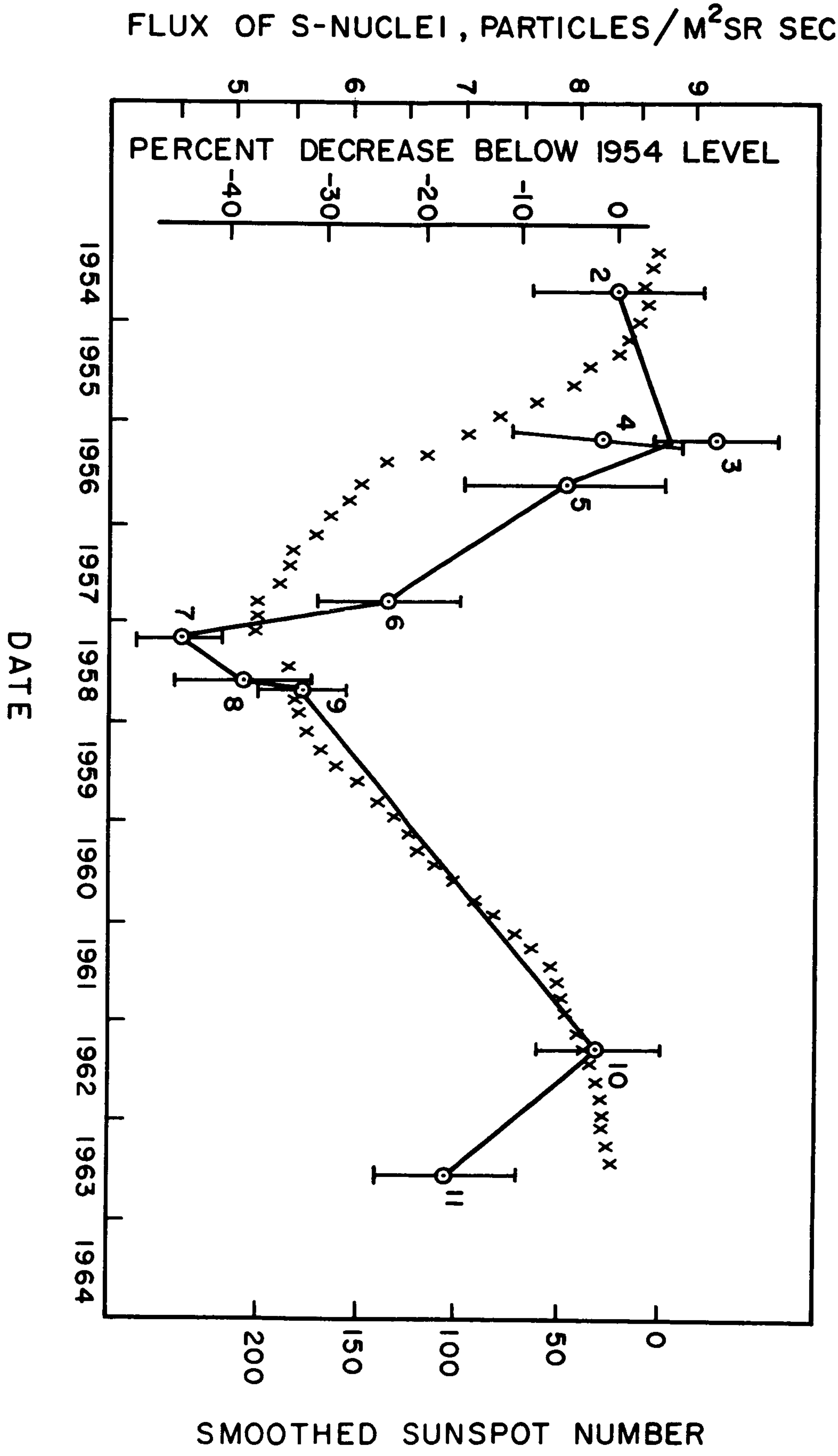


(a)

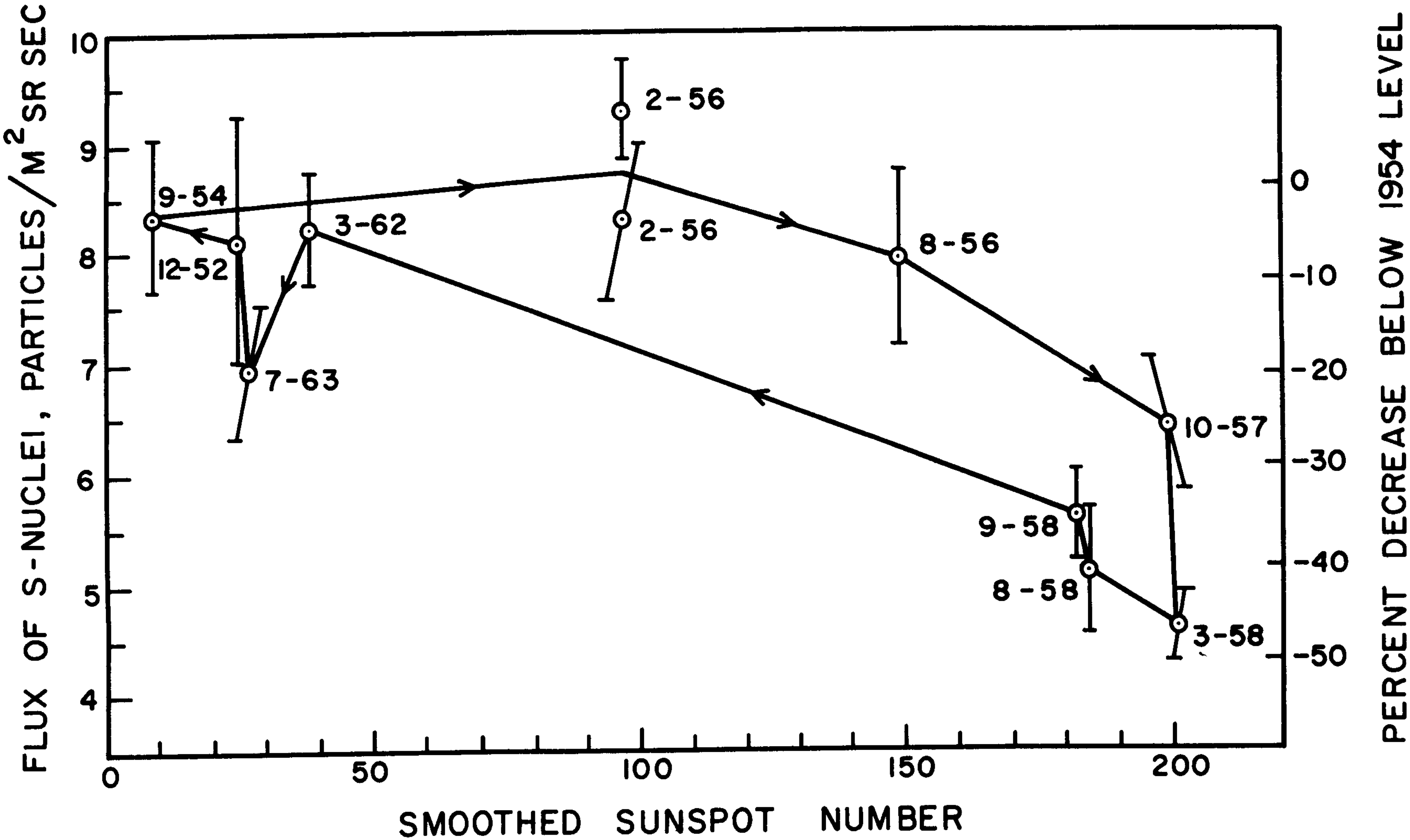


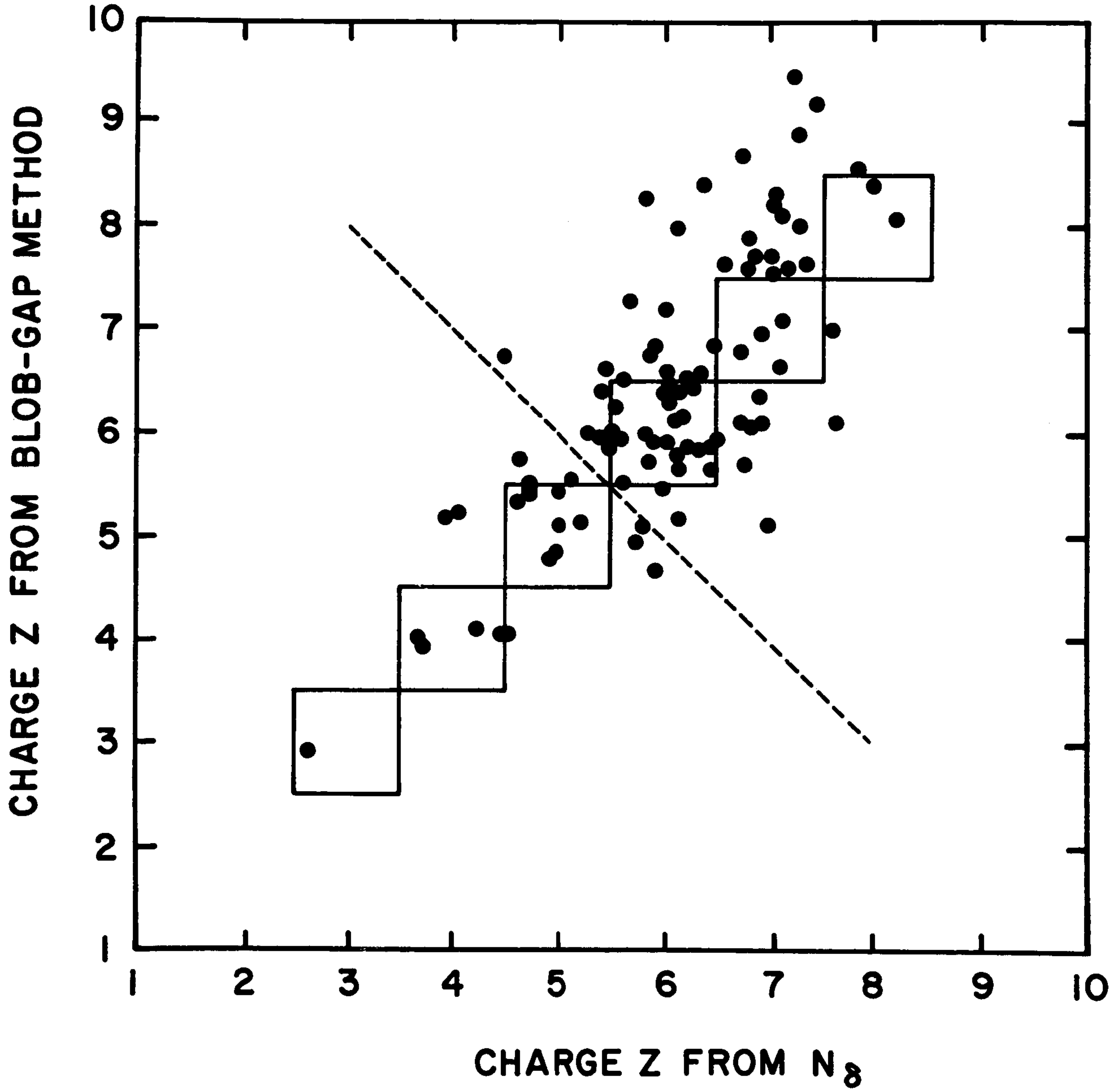
(b)

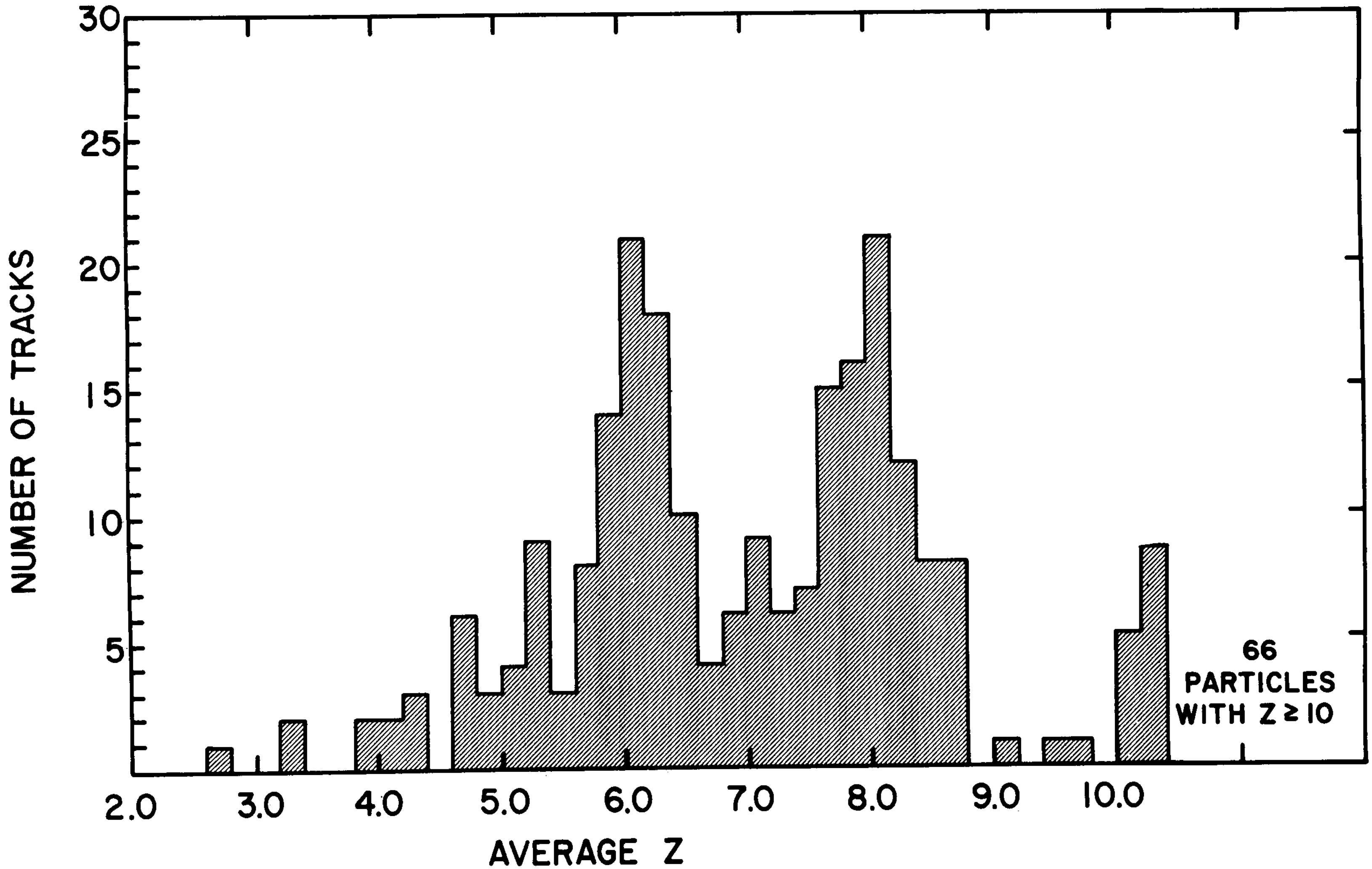

R ≥ 4.8 BV
FLUX OF S-NUCLEI, PARTICLES/M²SR SEC
MT. WASHINGTON NEUTRON MONITOR
0
2
4
6
8
10
1800
2000
2200
2400
2600



FLUX OF S-NUCLEI, PARTICLES/M²SR SEC
5
6
7
8
9
PERCENT DECREASE BELOW 1954 LEVEL
-40
-30
-20
-10
0
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
DATE
2
3
4
5
6
7
8
9
10
11
200
150
100
50
0
SMOOTHED SUNSPOT NUMBER


FLUX OF S-NUCLEI, PARTICLES/M^{2}SR SEC
PERCENT DECREASE BELOW 1954 LEVEL
SMOOTHED SUNSPOT NUMBER
10
9
8
7
6
5
4
0
-10
-20
-30
-40
-50
0
50
100
150
200
9-54
12-52
7-63
3-62
2-56
2-56
8-56
10-57
9-58
8-58
3-58


CHARGE Z FROM BLOB-GAP METHOD
CHARGE Z FROM N_δ
1
2
3
4
5
6
7
8
9
10


NUMBER OF TRACKS
30
25
20
15
10
5
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
AVERAGE Z
66
PARTICLES
WITH Z ≥ 10